

Interannual Variability of Ozone and Ultraviolet Exposure

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Abstract Annual zonal averages of ozone amounts from Nimbus-7/TOMS (1979 to 1992) are used to estimate the interannual variability of ozone and UVB (290 - 315 nm) irradiance between $\pm 60^\circ$ latitude. Clear-sky interannual ozone and UVB changes are mainly caused by the Quasi Biennial Oscillation (QBO) of stratospheric winds, and can amount to $\pm 15\%$ at 300 nm and $\pm 5\%$ at 310 nm (or erythemal irradiance) at the equator and at middle latitudes. Near the equator, the interannual variability of ozone amounts and UV irradiance caused by the combination of the 2.3 year QBO and annual cycles implies that there is about a 5-year periodicity in UVB variability. At higher latitudes, the appearance of the interannual UVB maximum is predicted by the QBO, but without the regular periodicity. The 5-year periodic QBO effects on UVB irradiance are larger than the currently evaluated long-term changes caused by the decrease in ozone amounts.

Introduction

The amount of UVB ultraviolet radiation (290 to 315 nm) penetrating to the Earth's surface is reduced by ozone absorption, aerosols, clouds, and Rayleigh scattering in the atmosphere. UVA irradiances (315 to 400 nm) are not significantly affected by ozone changes because of their small ozone absorption coefficients α_λ . Analysis of the ozone-amount time series [Stolarski et al., 1991; Herman et al., 1991] have shown that the major persistent sources of ozone variability are the annual cycle, the 2.3 year quasi-biennial oscillation cycle (QBO) (see, for example, Bowman [1989]), and the 11.5 year solar cycle [Hood, 1997; Zerefos et al., 1997, 1999; Calvo et al., 1995, and references therein].

A similar analysis for cloud and scene reflectivity (related to cloud transmission of UV radiation) shows that there is little effect from QBO, but that there is a significant 11.5 year solar cycle effect and ENSO (El Nino Southern Oscillation) effect [Herman et al., 2000]. Other sources of reflectivity variability arise from volcanic aerosol effects [Solomon et al., 1996] and shorter period perturbations of the atmosphere [Randel and Cobb, 1994].

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In this paper, ozone and reflectivity data (for cloud transmittance of UV radiances) from Nimbus-7/TOMS (1979 to 1992) are used to obtain the interannual variability of ozone and ultraviolet irradiances (300 nm and 310 nm) at the ground as a function of latitude. The results for 300 nm and 310 nm irradiances are compared with statistical time-series analysis to validate the identification of the main variability with the QBO. Using radiative transfer solutions for clear and cloudy atmospheres, the variability of annual UVB irradiance is derived for 60°S to 60°N zonal means in 2° latitude bands.

Data and Methodology

UV irradiances are determined from multiple-scattering radiative transfer calculations [Dave, 1965] using ozone values Ω obtained from TOMS measured radiances I_λ and cloud reflectivities R_{380} , within a Rayleigh scattering atmosphere over a low reflectivity surface [Herman and Celarier, 1997]. The attenuation of the surface radiation by clouds is estimated using the simplified cloud-transmittance model of Eck et al. [1995]. Defining C_T as the ratio of cloudy-sky to clear-sky transmittance $T_{\text{CLOUD}}/T_{\text{CLEAR}}$, the Eck et al. [1995] model is

$$C_T = [1 - (R_{380} - 0.05)/0.9] \quad 0.05 \leq R_{380} \leq 0.5 \quad (1)$$

$$C_T = 1 - R_{380} \quad R_{380} > 0.5$$

More accurate cloud transmittance models could be used without affecting the results of this study [Krotkov et al., 1999; Herman et al., 1999]. Since all of the results are based on annual zonally averaged ratios of radiances from different years, seasonal solar-zenith angle effects and ground reflectivity differences [Herman and Celarier, 1997] approximately cancel.

An approximation to the fractional changes in irradiance with fractional changes in total column ozone amount is given by the Radiation Amplification Factor (RAF) for irradiances I [Madronich 1993]. Comparisons with radiative transfer solutions including multiple scattering show that the approximation is highly accurate [Herman et al., 1999]

$$\frac{\Delta I}{I} = -\alpha \Omega \sec(\theta) \frac{\Delta \Omega}{\Omega} = -K \frac{\Delta \Omega}{\Omega} \quad (2)$$

where Ω is the total ozone amount in DU. For the daily exposure, radiative transfer calculations show that $K(300 \text{ nm}) \sim 3 \sec(\theta_{\text{Noon}})$ and $K(310 \text{ nm}) \sim \sec(\theta_{\text{Noon}})$. Because of this relationship, the changes in UVB or erythral irradiance and exposures will inversely track the changes in daily and longer term changes in ozone amounts (e.g., the QBO effect in ozone will also appear inversely in I)

In order to identify the sources of interannual variability, we incorporate a regression trend model similar to that used by Stolarski et al. [1991], but including an additional total ozone dynamical surrogate $P(t)$:

$$\Omega(t) = \alpha + \beta t + \gamma Q_{\text{QBO}}(t) + \delta S_{\text{solar}}(t) + \epsilon P(t) + R(t) \quad (3)$$

In (3), t is the month index ($t=1,2,\dots,168$), α , β , γ , δ and ϵ are time-dependent regression coefficients, each one given as a constant plus 12-month, 6-month, and 4-month cosine and sine harmonic series as defined by Randel and Cobb [1994]. The error in this model is the residual series $R(t)$, α is the seasonal fit, and the ozone trend is given by the coefficient β . $Q_{\text{QBO}}(t)$ in (3) is the quasi-biennial oscillation proxy derived from Singapore (1°N , 140°E) zonal winds using the method of Randel et al. [1995]. Their representation of $Q_{\text{QBO}}(t)$ involved the empirical orthogonal function (EOF) approach introduced by Wallace et al. [1993]. $S_{\text{solar}}(t)$ represents the solar proxy (10.7 cm solar-flux time series). In this study, deseasonalized and linearly detrended global brightness temperatures from the Microwave Sounding Unit channel 4 (MSU4) (half vertical weighting function response near 40 and 150 hPa, mean near 90 hPa) were used for the optional surrogate $P(t)$.

The major components contributing to ozone interannual variability can be obtained by systematically subtracting the 14-year average annual cycle from each year's ozone time series, removing the linear trend, subtracting a solar cycle term modeled on the 10.7 cm solar flux, and then removing the QBO variability modeled from Singapore zonal winds [Herman et al., 1991]. This can be done sequentially for each component or simultaneously [Stolarski et al., 1991] as in the present study by a statistical least squares fit to variations in the ozone data (see equation 3). Once the model coefficients have been obtained, each contributing component can be studied separately.

Interannual Ozone Variability

Year-to-year variability in ozone amounts can be obtained directly by subtracting each year's zonal average ozone amounts from the preceding year, as a function of latitude. In Figure 1 the results are summarized in annual zonal averages of the differences (see the right half of Figure 1). As shown in the left half of Figure 1, the QBO term from the model described in Equation 3 accounts for most of the interannual variability up to latitudes of about 55° .

At the equator, the interannual difference is positive whenever the QBO westerlies overlie easterlies (westerly shear) from 10 hPa to 70 hPa for the first half of the QBO cycle and easterlies above westerlies for the second half. The westerly shear results in downward secondary circulation along the equator (increasing ozone) and the easterly shear causes upward secondary circulation (decreasing ozone). At subtropical and middle latitudes the secondary circulation is reversed, causing the opposite effect in total-ozone amount. The secondary circulation pattern reverses approximately every 2.3 years, producing a reversal in the ozone percentage differences shown in Figure 1. During the years 1981 to 1984 and 1986 to 1988, percentage differences in low latitudes were small. A key point is that the QBO interannual differences have about a 5-year period.

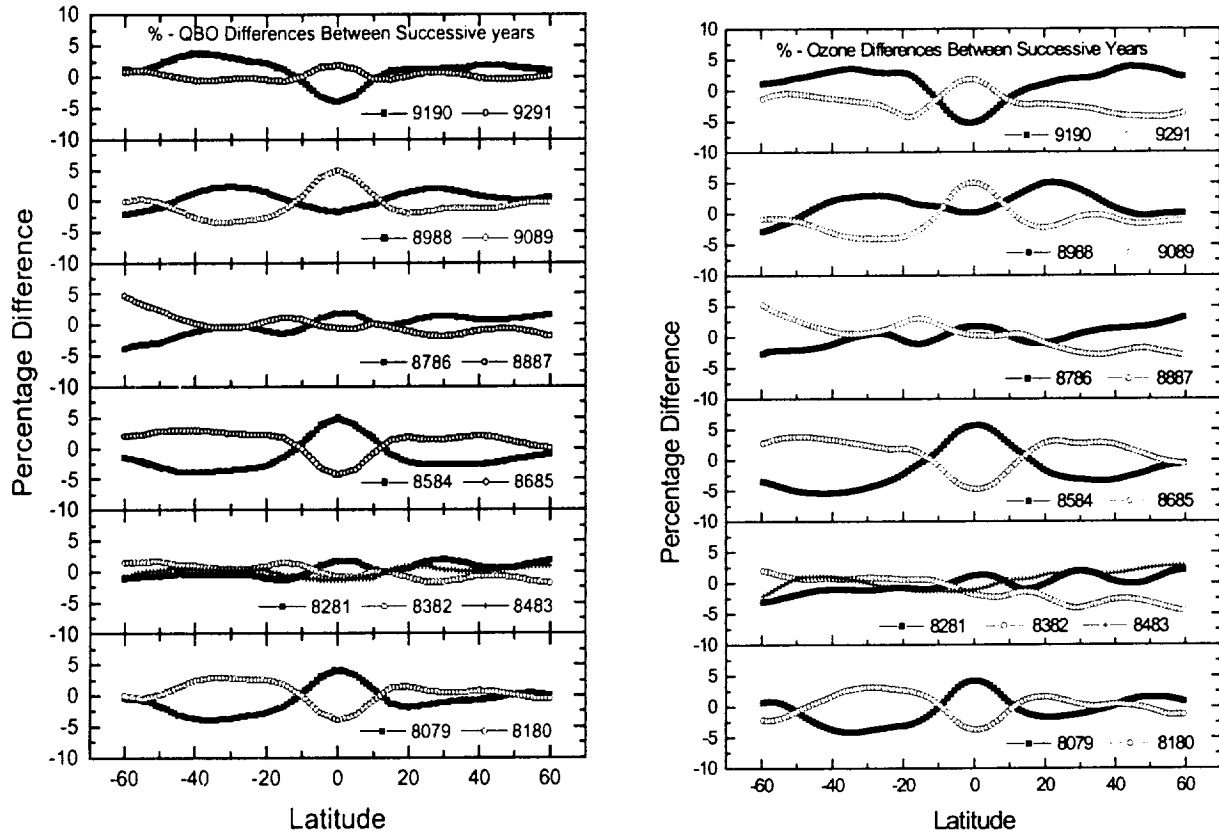


Figure 1 Differences for successive years between annual zonally-averaged ozone amounts for the years 1979 to 1992 (Right Half) and the QBO term from a statistical fit to the ozone data (Left Half). The darker curve in each frame represents the earlier pair of years. The caption within each frame indicates the years entering into the differences. The symbol 8079 means $100[O_3(1980) - O_3(1979)]/O_3(1979)$.

The latitudinal dependence of the interannual variability of ozone is quite similar to that of the QBO term obtained from the statistical model. Most of the features in the modeled ozone data are well reproduced except at high latitudes near 60° and greater. In particular, reversal of the QBO effect in interannual ozone differences between low- and mid-latitudes is almost the same as shown in the ozone-amount data. The percent differences between the observed interannual variability and the amount arising from QBO term in Equation 3 show that the other terms in Equation 3 must be retained for a full description of ozone variability.

Annual Variability of UV-B Exposure

At the equator and middle latitudes the average interannual ozone variation can amount to $\pm 5\%$ between successive years. Based on K (Radiation Amplification Factor) for irradiances at moderate solar zenith angles, the changes in 300 nm irradiances are substantially larger than at 310 nm for a given change in ozone amount. K is approximately proportional to the ratio of the ozone absorption coefficients $\alpha_\lambda(300)/\alpha_\lambda(310)$. For the erythemally-weighted irradiance, CIE

action-spectra weighted integral from 290 nm to 400 nm [McKinlay and Diffey 1987], the sensitivity to ozone change is approximately the same as for 310 nm.

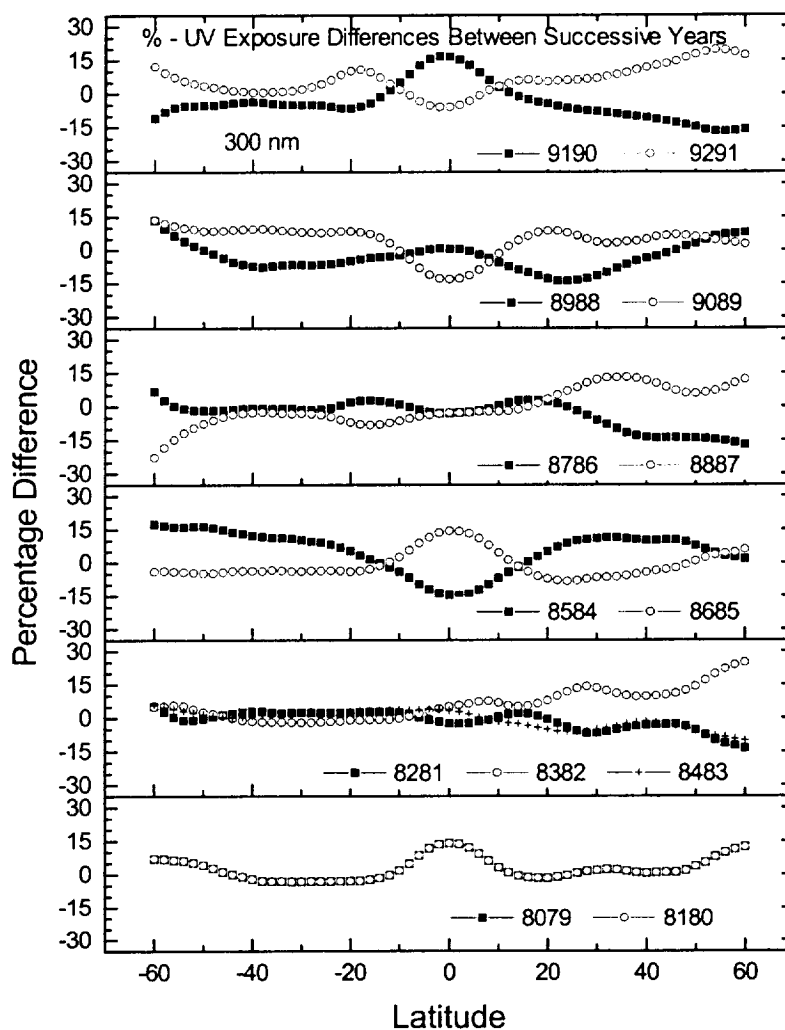


Figure 2 Percent differences for successive years of 300 nm UV annual exposure for clear sky conditions. The uv-exposures for 1979 are omitted as that year's data has too many missing days.

In Figures 2 and 3, the UV-B exposures are computed from solutions of the multiple scattering radiative transfer equation [Dave, 1965] using ozone amounts and cloud reflectivities measured by TOMS and at every 1° latitude \times 1.25° longitude grid point. The UV exposure E is defined as the integral over daylight hours of the UV irradiance at the Earth's surface. Because of the decrease in the intensity of the primary solar-flux beam with increasing solar zenith angle θ during the day, the main contribution to the exposure comes from times near noon ($\sim \exp(-$

$\alpha \Omega \sec \theta$)). Since the percent changes between successive years for the clear-sky 300 nm and 310 nm UV-B annual exposure (Figures 2 and 3) are modulated by ozone absorption, the changes are inverse to the changes in ozone amount (Figure 1) as indicated in Equation 2.

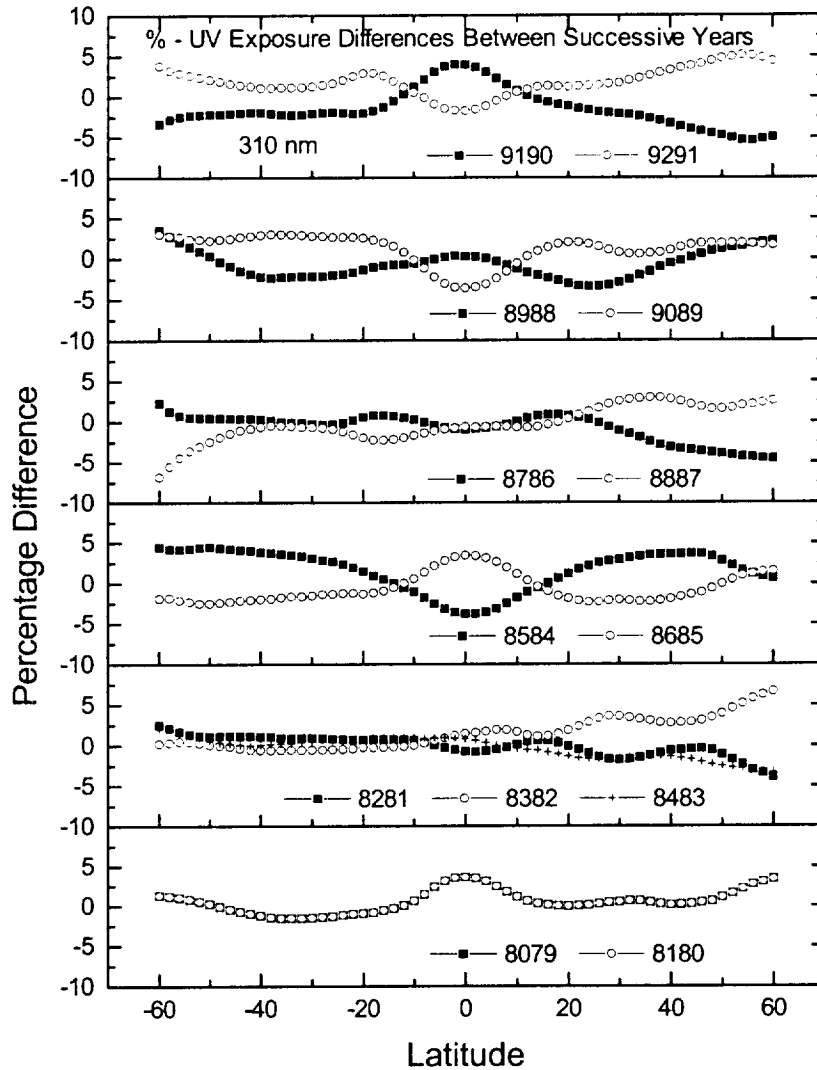


Figure 3 Percent differences for successive years of 310 nm UV annual exposure for clear sky conditions. The uv-exposures for 1979 are omitted as that year's data has too many missing days.

For 310 nm, the ratio of proportionality constants $K_{300}/K_{310} \sim 3$ (see equation 2 where $K = \alpha_{\lambda} \Omega \sec(\theta)$). Shorter wavelengths λ will have $K_{\lambda}/K_{310} \gg 1$ and longer wavelengths, $K_{\lambda}/K_{310} \ll 1$, roughly in proportion to the ozone absorption coefficient ratio to that at 310 nm. As with irradiance, exposure also a dependence on the noontime solar zenith angle for a specified latitude and season.

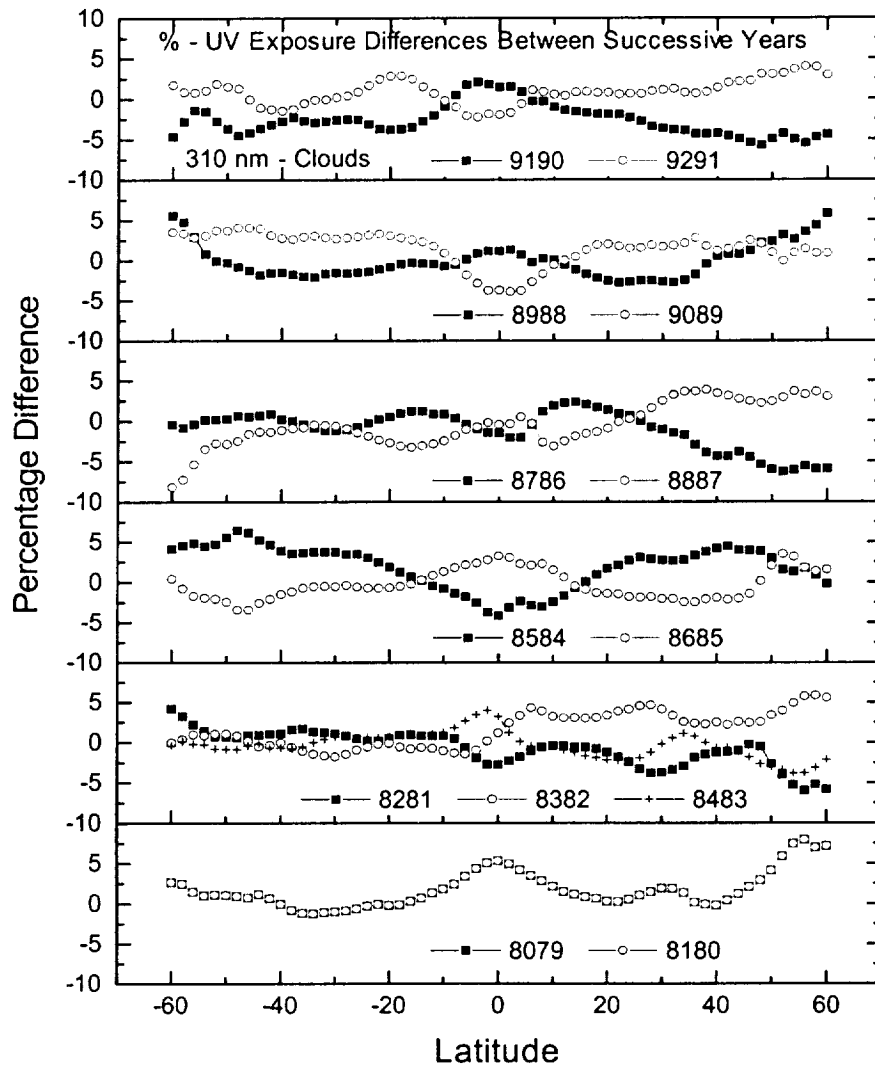


Figure 4 The same as Figures 3 for 310 nm (zonal average and annual average), but with cloud effects included.

When the effects of cloud cover are included in the zonally averaged annual exposure estimate, based on the TOMS reflectivity measurements (Herman et al., 1966; Herman et al., 1999; Krotkov et al., 1999), the results are substantially the same (see Figure 4). There are small percentage differences caused by cloud cover variability between successive years that are less than the QBO effect. The effect of clouds is to reduce the daily and annual UV-B transmittance to the ground and increase its day-to-day variability. If the exposure is computed along a meridian, instead of a zonal average, then the cloud-induced differences between successive years are larger than for zonal averages. This is because annually repeating cloud patterns have small shifts in their geographical locations from year-to-year, causing substantial differences in surface UV-B flux. Examples of the local cloud induced variability of UV irradiances is shown

in Herman et al. [2000].

In the latitude range 40°S to 40°N, year-to-year UVB variabilities caused by cloudiness and the QBO are both larger than long-term (decadal) UVB changes caused by decreases in ozone, since the start of the global TOMS record [Herman et al., 1996; 1999]. The decadal trend analysis of Nimbus-7/TOMS ozone data shows that there are no statistically significant (2 standard deviations) annual trends between $\pm 40^\circ$ latitudes, and especially no trends in the tropical region $\pm 10^\circ$ where the clear-sky UV exposure is very high because of the nearly overhead sun. The interannual variability caused by the QBO effect in these regions can easily reach 10% at 310 nm between the maximum and minimum exposure amounts for different years. The same magnitude of variability is calculated for the erythema exposure. For those years corresponding to the maximum UV exposure, the risk of biological damage is increased substantially. This effect is repeatable, occurring approximately every 5 years (e.g., 1981, 1986, 1991, etc.).

At higher latitudes, the effect diminishes, going to zero at about $\pm 10^\circ$ latitude and then increasing again into the middle latitudes. At middle latitudes the periodicity is less pronounced because of the interference of other dynamical effects mixed in with the QBO effect. The percent differences in midlatitude surface UVB at 310 nm for successive years can be as much as 10%, because of the QBO and other interannual sources. The corresponding value for 300 nm is about 25%.

As shown by Herman et al. [1996, 2000], the largest decadal increases in exposure occur in spring months, between latitudes 35° and 60° in both hemispheres, and amount to about +4% per decade at 310 nm. For 300 nm, exposure percentage changes are larger by a factor of about three. Trends in extra-tropical 300 nm UV-B exposures analyzed by Herman et al. [1996] were around +10% per decade during spring.

Determinations of clear-sky long-term changes from currently available well-calibrated ground-based measurements are made more difficult since QBO driven changes in surface UV-B are larger than the UV trends expected from long-term changes in ozone amount. The monthly QBO effects must be removed from the data record available from ground-based measurements prior to the estimation of trends. Since the calculated UV irradiance from TOMS ozone data spans 14 years (5 QBO cycles), the annual cycle, QBO, and solar cycle effects are easily removed from long-term UV trends.

Summary

The year to year differences between zonal averages of ozone amount, from Nimbus-7/TOMS (1979 to 1992), cause a periodic (~5-year) interannual variability of UVB (290 - 315 nm) exposure to solar radiation between $\pm 60^\circ$ latitude. As shown from statistical modeling, clear-sky interannual UVB changes can be ascribed mainly to the Quasi Biennial Oscillation (QBO) of the stratospheric winds in the 30 hPa to 50 hPa (~21-25 km) altitude range. The QBO

oscillations can cause interannual changes in UVB exposure of $\pm 15\%$ at 300 nm and $\pm 5\%$ at 310 nm (or erythema exposure) at the equator and at middle latitudes. There are larger interannual changes in UVB associated with dynamical effects at higher latitudes. When clouds effects are included, the general latitudinal structure of the interannual variability is maintained. At the equator, the interannual variability of ozone amounts and UV exposure caused by the combination of the 2.3 year QBO and annual cycles implies that there is about a 5-year periodicity in UVB variability caused by dynamical effects. At higher latitudes, the appearance of the interannual UVB maximum is predicted by the QBO, but without the regular periodicity. The 5-year periodic QBO effects on UVB irradiance are larger than the currently evaluated long-term changes caused by the decrease in ozone amounts between $\pm 60^\circ$ latitudes.

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